Sea Level Rise Potential for the City of Alexandria, Virginia

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Introduction

The City of Alexandria, Virginia, (City) has experienced repeated and increasingly frequent flooding events attributable to old infrastructure, inconsistent design criteria, and perhaps climate change. The purpose of this project is to provide a program that, over a period of up to 5 years, will analyze storm sewer capacity issues, identify problem areas, develop and prioritize solutions, and provide support for public outreach and education.

The purpose of the first task is to review and propose revisions to the City's stormwater design criteria, through a series of four subtasks.

The purpose of subtask 1.4 is to provide the City of Alexandria with a range of potential sea level rise based on appropriate climate change scenarios. The subtask analyzes historical records for trends and uses the

SimCLIM application to quantitatively determine specific sea level rise in the Chesapeake Bay and the Potomac River near Alexandria.

The other three Task 1 subtasks that will develop recommendations for updating the City's stormwater design criteria include the following:

- Subtask 1.1 - Comparison of Alexandria's Storm Design Criteria to Neighboring Jurisdictions
- Subtask 1.2 – Updated Precipitation Frequency Results and Synthesis of New IDF (intensity, duration, and frequency) Curves
- Subtask 1.3 – Rainfall Frequency and Global Climate Change Model Options for Study Area

Executive Summary and Recommendations

Results from five global circulation models using low, medium, and high greenhouse gas emission scenarios were used to generate projected changes in mean high water and mean higher high water (MHHW) at the Washington D.C. gauge near the City of Alexandria for the years 2050 and 2100.

The projected median sea level rise from the five general circulation models (GCM) and three greenhouse gas scenarios ranges from 1.76 to 2.44 feet North American Vertical Datum (NAVD) by the year 2100. The 10 and 90 non-exceedance percent ranges are 1.33 and 3.35 feet NAVD, respectively.

The projected median MHHW sea level rise from the five GCMs and three greenhouse gas scenarios ranges from 3.35 to 4.05 feet (NAVD) by the year 2100. The 10 and 90 non-exceedance percent ranges are 2.94 and 4.96 feet (NAVD) respectively.

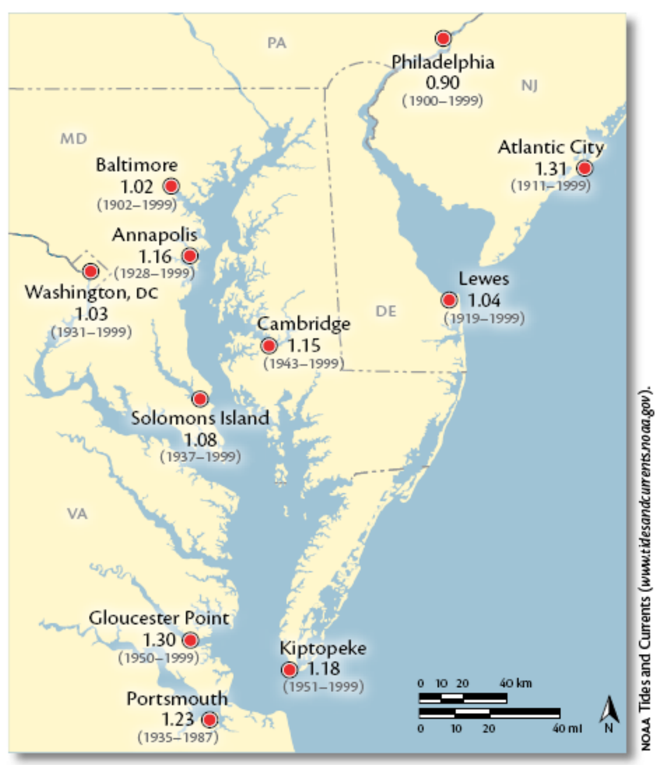
A review of relevant literature on sea level rise in the Chesapeake Bay area was conducted. The literature indicated a range of sea level rise from 2.7 to 3.4 feet in one study, and from 1.6 to 4.6 feet in another study by 2100. The literature generally corroborates the projections developed in this study.

Therefore, it is projected that future infrastructure planning take into account possible increases in sea level of between 3.3 and 4.0 feet for MHHW, in addition to water levels projected in the Potomac River, because of storm surge and flood flows in the Potomac River. With current 10-year water surface elevations in the Potomac River of approximately 5.4 feet NAVD, the projected water surface for the 10-year event with sea level rise is between 8.7 and 9.4 feet NAVD. Similarly, with current 100-year water surface elevations in the Potomac River of approximately 9.9 feet NAVD, the projected water surface for the 100-year event with sea level rise is between 12.2 and 13.9 feet NAVD.

FIGURE 1

Rates of Sea Level Rise in Chesapeake and Delaware Bays Region.

Data are from tide gauges and the period of time they cover is in parentheses. (MCCC, 2008)



Sea Level Rise Literature Review

A large number of state, federal, and private sector studies has been published that deal with sea level rise in the Mid-Atlantic States. Relevant studies are summarized below.

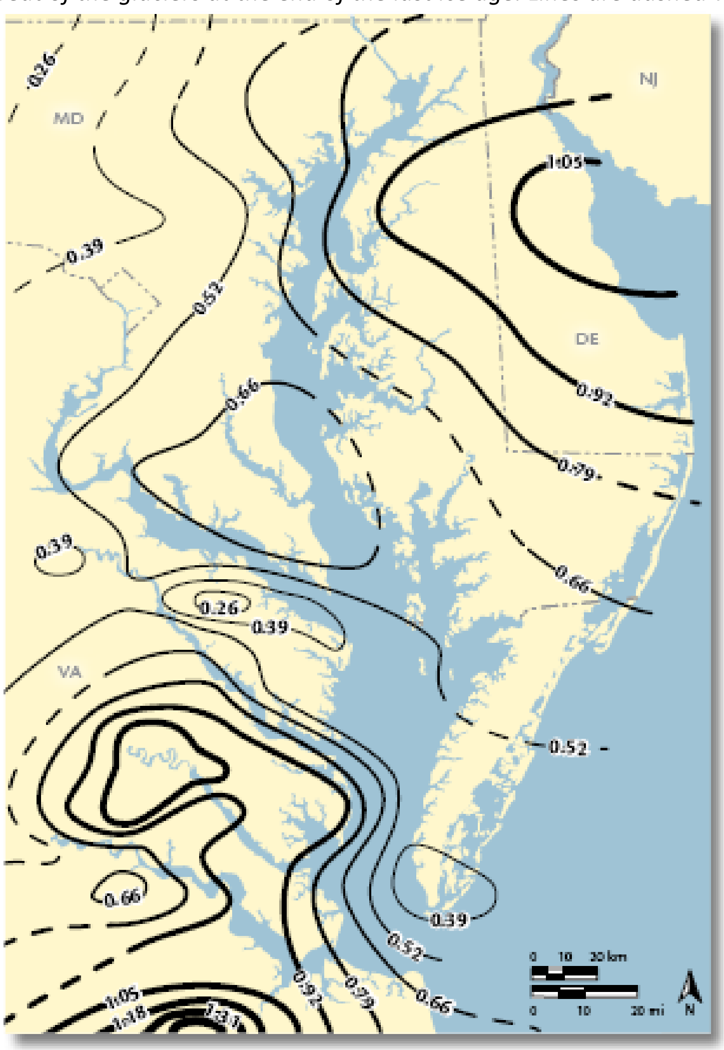
Maryland Commission on Climate Change (MCCC) and Adaptation and Response Working Group

The Maryland Commission Climate Change (MCCC) *Comprehensive Strategy for Reducing Maryland's Vulnerability to Climate Change, Phase I: Sea Level Rise and Coastal Storms* provides a comprehensive overview of research and strategies to minimize impacts of sea level rise and storms on the state (MCCC, 2008). The report states that, although the rapid rate of sea level rise that occurred over the past 5,000 years has slowed, historical tide-gauge records show that levels are still rising and have increased by 1 foot within Maryland's coastal waters in the last 100 years (Figure 1). Such a rate of rise is nearly twice that of the global average over the same period. The region is also experiencing more of a relative sea level rise than other parts of the world as a result of naturally occurring regional land subsidence, as shown in Figure 2.

FIGURE 2

Rates of Land Subsidence in the Chesapeake Bay Region

Subsidence in this region is mostly a result of postglacial rebound or readjustment (sinking) of land elevations since the retreat of the glaciers at the end of the last ice age. Lines are dashed where values are inferred. (MCCC, 2008)



The report states that MCCC Scientific Technical Working Group assessed the 2007 Intergovernmental Panel on Climate Change (IPCC) global sea level rise projections, along with regional land subsidence variables, and provided a conservative estimate that by the end of the century, Maryland could experience a relative sea level rise of 2.7 feet under a lower-emissions scenario, and as much as 3.4 feet under the higher-emission scenario.

Coastal Sensitivity to Sea Level Rise:

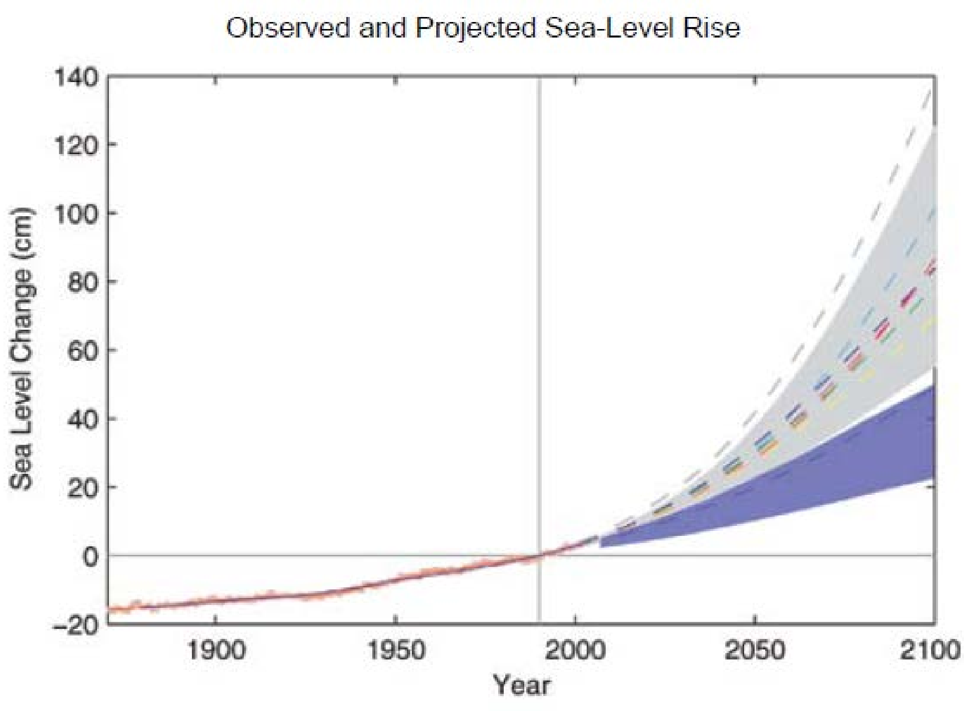
A Focus on the Mid-Atlantic Region Final Report, Synthesis and Assessment Product 4.1, Climate Change Science Program (CCSP) / U.S. Environmental Protection Agency (EPA)

The U.S. Climate Change Science Program (CCSP) publishes wide variety of climate change-related reports for specific topic areas synthesized from peer-reviewed journals.

The CCSP's guiding vision is to provide the nation and the global community with the science-based knowledge needed to manage the risks and capture the opportunities associated with climate and related environmental changes. The synthesis and assessment products are important steps toward achieving that vision and help to translate the CCSP's extensive observational and research database into informational tools that directly address key questions being asked of the research community.

The publication mentions the IPCC Fourth Assessment Report (IPCC, 2007) estimates of global sea level rise of 18 to 59 centimeters (cm) (7 to 23 inches) over the next century; however, possible increased meltwater contributions from Greenland and Antarctica were excluded (Meehl et al., 2007; IPCC, 2007). The IPCC projections (Figure 3) represent a "likely range," which inherently allows for the possibility that the actual rise may be higher or lower.

FIGURE 3
Plot in Centimeters (cm) Rise overtime of Past Sea Level Observations and Several Future Sea-Level Projections to the Year 2100
The blue-shaded area is the sea level rise projection by Meehl et al. (2007) corresponding to the A1B emissions scenario, which forms part of the basis for the IPCC (2007) estimates. The higher gray and dash line projections are from Rahmstorf (2007). (Modified from: Rahmstorf, S., 2007: A semi-empirical approach to projecting future sea level rise. Science, 315[5810], 368-370).



Recent observations suggest that sea level rise rates could already be approaching the higher end of the IPCC estimates (Rahmstorf et al., 2007; Jevrejeva et al., 2008). This is because potentially important meltwater contributions from Greenland and Antarctica were excluded because of limited data and an inability at that time to adequately model ice flow processes. It has been suggested by Rahmstorf et al. (2007) and other climate scientists that a global sea level rise of 1 meter (3 feet) could occur within this century if increased melting of ice sheets in Greenland and Antarctica is added to the factors included in the IPCC estimates. Therefore, thoughtful precaution suggests that a global sea level rise of 1 meter by the year 2100 should be considered for future planning and policy discussions.

The CCSP report also mentions that on the Virginia side of the Potomac River, many coastal homes are along bluffs, some of which are eroding (Bernd-Cohen and Gordon, 1999). Lewisetta is one of the larger vulnerable communities along the Potomac River. Water in some ditches rise and fall with the tides, and some areas drain through tide gates. With a fairly modest rise in sea level, one could predict that wetlands could begin to take over portions of people's yards, the tide gates could close more often, and flooding could become more frequent. Somewhat higher in elevation than Lewisetta, Old Town Alexandria and Belle Haven (Fairfax County) both flood occasionally from high levels in the Potomac River.

Climate Change and the Chesapeake Bay – Chesapeake Bay Program Science and Technology Advisory Committee

The Chesapeake Bay Program Science and Technical Advisory Committee published a report in September 2008 that focused on projected sea level rise and the impacts of the rise on tidal range (Pyke 2008).

The Sea Level Section (Section 2.5 of Pyke, 2008) of the report references work by Rahmstorf (2007) describing that "rates of historic sea level rise calculated with climate models tend to be too low, most likely because ice sheet dynamics are poorly understood. He developed a semi-empirical approach that predicts global sea level increases of 700 to 1000 mm [millimeter] by 2100 for a range of scenarios spanning B1 to A1FI. Allowing for errors in the climate projections and in the semi-empirical sea level-rise model, the projected range increases to 500 to 1400 mm. Adding a Chesapeake Bay local component of 2 mm/yr results in sea level increases of approximately 700 to 1600 mm by 2100."

The Circulation Section (4.1) of the report references work by Zhong et al. (2008) describing the only numerical modeling study to consider the impact of climate change on Chesapeake Bay circulation. This research suggested that the tidal range near Baltimore, Maryland (in the upper portion of the Bay), will increase by 15 to 20 percent if sea level increases by 1 meter. Zhong et al. (2008) argued that friction reduction and the Chesapeake Bay moving closer to its resonant period will cause this amplitude increase.

Sea Level Rise and Coastal Habitats in the Chesapeake Bay Region, National Wildlife Federation (NWF)

The National Wildlife Federation (NWF) used the Sea Level Affecting Marshes Model (SLAMM) to assess changes in tidal marsh area and habitat type in response to sea level rise (Park et al., 1989). The SLAMM 5 was run for the emissions and fixed-rate scenarios shown in Table 1. The results indicate up to a 69 cm rise in eustatic sea level rise by 2100 using the A1B Max emissions scenario. The report does not mention the GCMs used for this study.

TABLE 1
SLAMM 5 was Run using the Following IPCC (2001) and Fixed-Rate Scenarios (NWF, 2008)

Scenario	Eustatic SLR by 2025	Eustatic SLR by 2050	Eustatic SLR by 2075	Eustatic SLR by 2100	Protect Developed Land
B1 Mean	8 cm (3.1 in)	15 cm (5.9 in)	23 cm (9.1 in)	31 cm (12.2 in)	NO
A1B Mean	8 cm (3.1 in)	17 cm (6.7 in)	28 cm (11 in)	39 cm (15.4 in)	YES
A1f1Mean	8 cm (3.1 in)	17 cm (6.7 in)	32 cm (12.6 in)	49 cm (19.3 in)	NO
A1B Max	13 cm (5.1 in)	28 cm (11 in)	48 cm (18.9 in)	69 cm (27.2 in)	YES
1 meter	18 cm (7.1 in)	41 cm (16.1 in)	70 cm (27.6 in)	100 cm (39.4 in)	YES
1.5 meter	28 cm (11 in)	61 cm (24 in)	105 cm (41.3 in)	150 cm (59.1 in)	YES
2 meters	37 cm (14.6 in)	82 cm (32.3 in)	140 cm (55.1 in	200 cm (78.7 in)	NO

Additional Sea-Level Rise Studies

Recent research by Overpeck et al. (2006) compared arctic climate during the last interglacial period with conditions projected to occur during the 21st century under a business-as-usual emissions (A2) scenario and resulted in sea level rise estimates on the order of 0.8 to 0.9 meter. Overpeck et al. (2006) found that the arctic will be substantially warmer before the end of the 21st century than it was during the last interglacial period. This suggests that similar areas of Greenland could melt, raising sea level by at least 2 meters. Just how rapidly this melting might occur is a key question, with traditional models suggesting that it could take a thousand years. The accelerating pace of melting recently observed, suggests that this might take only centuries.

Research by Rohling et al. (2007) used a combination of a continuous high-resolution sea level record based on the stable oxygen isotopes of planktonic foraminifera from the central Red Sea, and age constraints from coral data to estimate rates of sea level change during the last interglacial period, Marine Isotope Stage-5e (MIS-5e). Rohling et al. (2007) found that a 1.6-meter global sea level rise per century would correspond to disappearance of an ice sheet the size of Greenland in roughly 4 centuries (modeling suggests 1,000 years or more).

During MIS-5e, such rates of sea level rise occurred when the global mean temperature was 2 degrees Celsius (°C) higher than today, as expected again by 2100. Using MIS-5e to gain insight into the potential rates of sea level rise as a result of further ice-volume reduction in a warming world, Rohling et al. (2007) data provide an observational context that underscores the plausibility of recent, unconventionally high projections of 1.0 ± 0.5 meter sea level rise by 2100.

Sources of Data, Quality Control, and Adjustments

Historical observed tide data were obtained from the National Oceanic and Atmospheric Administration (NOAA) Tides and Currents website (http://tidesandcurrents.noaa.gov/). NOAA's Center for Operational Oceanographic Products and Services (CO-OPS) provides the infrastructure, science, and technical expertise to collect and distribute tide, current, and water level data at a national level. Historical data from four stations in the Chesapeake Bay (Figure 4) with lengthy records were selected for review. The locations of these stations and the period of record for each are provided in Table 2.

FIGURE 4
Location of Four Selected Tide Gage Stations for Sea Level Rise Analysis Trend Analysis in the Chesapeake Bay Region

TABLE 2
Metadata Description of the Tide Stations used in the CH2M HILL Sea Level Rise Analysis

Selected Chesapeake Bay Tide Stations

Station ID	Location	State	Longitude	Latitude	Period of Record
8594900	Washington D.C.	MD/DC	77° 1.3' W	38° 52.4' N	1931 - Present
8575512	Annapolis	MD	76° 28.8' W	38° 59' N	1928 - Present
8574680	Baltimore	MD	76° 34.7' W	39° 16' N	1902 - Present
8632200	Kiptopeke	VA	75° 59.3' W	37° 9.9' N	1951 - Present

Highest tide, lowest tide, and mean sea levels were obtained at each station for their period of record. Values for Mean High Water (MHW), Mean Higher High Water (MHHW), Mean Low Water (MLW), and Mean Lower-Low Water (MLLW) were also obtained. The definition of each variable is presented in Table 3.

TABLE 3
NOAA Tide Station Datum Definitions

Acronym	Datum	Definition
MHHW[a]	Mean Higher-High Water	The average of the higher high water height of each tidal day
MHW	Mean High Water	The average of all the high water heights observed
MSL	Mean Sea Level	The arithmetic mean of hourly heights observed
MLW	Mean Low Water	The average of all the low water heights observed
MLLW*	Mean Lower-Low Water	The average of the lower low water height of each tidal day observed

[a]Some locations have diurnal tides--one high tide and one low tide per day. At most locations, there are semidiurnal tides--the tide cycles through a high and low twice each day, with one of the two high tides being higher than the other, and one of the two low tides being lower than the other.

Adapted From: NOAA Tides and Currents, http://tidesandcurrents.noaa.gov/datum_options.html

Data values (ft) were downloaded at a monthly time step relative to the North American Vertical Datum of 1988[1] (NAVD 88). A summary of missing data points for each station and variable is provided in Table 4.

TABLE 4
Summary of Missing Tide Data for Selected Stations for the CH2M HILL Study

		Missing Data					
		High Tide		Low Tide		Mean Sea Level	
Location	Period of Record Duration (Months)	Months	% Total	Months	% Total	Months	% Total
Washington D.C.	932	27	2.9%	28	3.0%	17	1.8%
Annapolis	964	46	4.8%	53	5.5%	29	3.0%
Baltimore	1278	24	1.9%	24	1.9%	2	0.2%
Kiptopeke	688	10	1.5%	9	1.3%	3	0.4%

[1] NOAA defines NAVD 88 as follows: *A fixed reference for elevations determined by geodetic leveling. The datum was derived from a general adjustment of the first-order terrestrial leveling nets of the United States, Canada, and Mexico. In the adjustment, only the height of the primary tidal bench mark, referenced to the International Great Lakes Datum of 1985 (IGLD 85) local mean sea level height value, at Father Point, Rimouski, Quebec, Canada was held fixed, thus providing minimum constraint. NAVD 88 and IGLD 85 are identical. However, NAVD 88 benchmark values are given in Helmert orthometric height units, while IGLD 85 values are in dynamic heights. See International Great Lakes Datum of 1985, National Geodetic Vertical Datum of 1929, and geopotential difference. NAVD 88 should not be used as Mean Sea Level.* (NOAA, 2009)

Sea Level Rise Components

Global sea level rise results mainly from the worldwide increase in the volume of the world's oceans that occurs as a result of thermal expansion of warming ocean water and the addition of water to the ocean from melting ice sheets and glaciers (ice masses on land). Relative sea level rise is measured directly by coastal tide gauges, which record both the movement of the land to which they are attached and changes in global sea level.

Global sea level rise can be estimated from tide gauge data by subtracting the land elevation change component. Thus, tide gauges are important observation instruments for measuring sea level change trends. However, because variations in climate and ocean circulation can cause fluctuations over 10-year periods, the most reliable sea level data are from tide gauges having records 50 years or longer and for which the rates have been adjusted using a global isostatic adjustment model (Douglas, 2001).Local sea level is relative and is determined by a number of factors, including Eustatic change in global ocean levels (as a result of thermal expansion of the ocean and melting of land-based ice).

At regional and local scales along the coast, vertical movements of the land surface can also contribute significantly to sea level change and the combination of global sea level and land-level change is referred to as "relative sea level" (Douglas, 2001). Thus, relative sea-level rise" refers to the change in sea level relative to the elevation of the land, which includes both global sea level rise and vertical movements of the land.

Historical Sea Level Rise

Data for four stations in the Alexandria, Virginia, region were downloaded from NOAA to determine sea level trends for the available period of record as shown in Table 5. Long-term trends for the four stations are similar in magnitude, as shown on Figure 5.

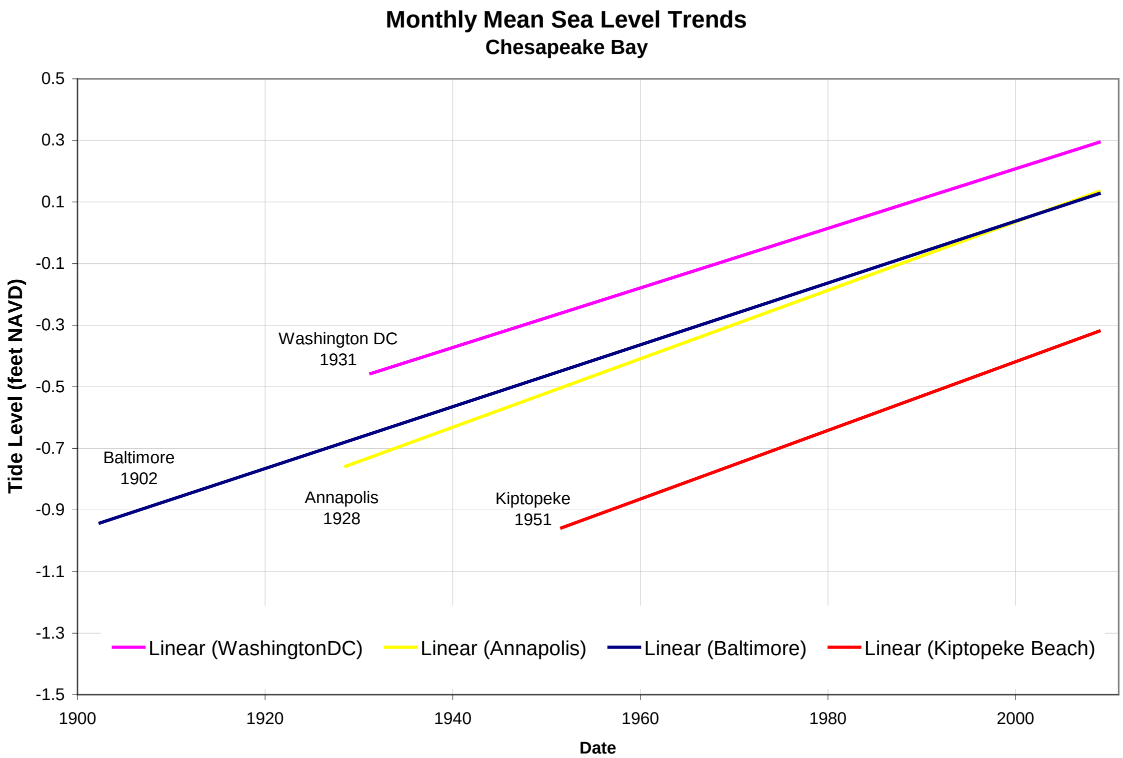
TABLE 5
Summary of Sea Level Trend for Selected Stations in Chesapeake Bay

Location	Station	Distance[a]	Period of Record	Change Over Time (ft / 100 years)
Washington D.C.	8594900	--	1924 - 2006	1.04
Annapolis	8575512	29.6 miles E	1928 - 2006	1.13
Baltimore	8574680	35.9 miles NE	1902 - 2006	1.01
Kiptopeke	8632200	130.1 miles SE	1951 - 2006	1.14

[a]Relative to Tidal Gage 8594900 at Washington, D.C.
Source: NOAA Tides and Currents, http://tidesandcurrents.noaa.gov/

FIGURE 5

Comparison of Historical Trends in Observed Monthly Sea Level at Four Stations in the Chesapeake Bay



Figures 6 through 9 show the monthly mean sea level for the four tide stations in the study without the regular seasonal fluctuations caused by coastal ocean temperatures, salinities, winds, atmospheric pressures, and ocean currents. The long-term linear trend is also shown, including its 95 percent confidence interval. The plotted values are relative to the most recent mean sea level datum established by CO-OPS.

FIGURE 6

Monthly Mean Sea Level Values, Long-Term Linear Trend, and 95 Percent Confidence Interval at Washington, D.C. (8594900)

Values adjusted to exclude regular seasonal fluctuations caused by coastal ocean temperatures, salinities, winds, atmospheric pressures, and ocean currents. The plotted values are relative to the most recent mean sea level datum established by CO-OPS. (NOAA, 2009)

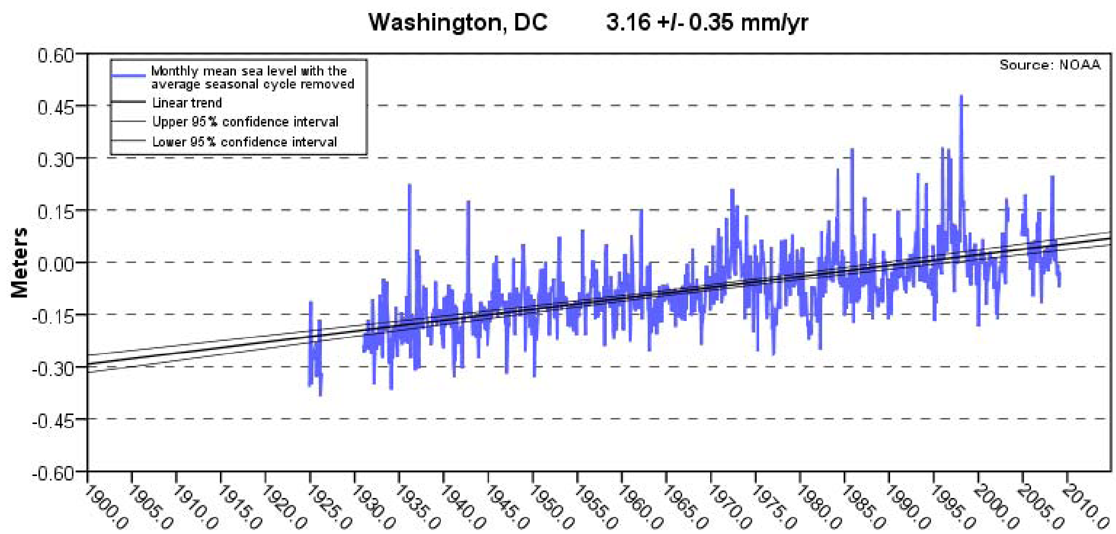


FIGURE 7

Monthly Mean Sea Level Values, Long-Term Linear Trend, and 95 Percent Confidence Interval at Annapolis, Maryland (8575512)

Values adjusted to exclude regular seasonal fluctuations caused by coastal ocean temperatures, salinities, winds, atmospheric pressures, and ocean currents. The plotted values are relative to the most recent Mean Sea Level datum established by CO-OPS. (NOAA, 2009)

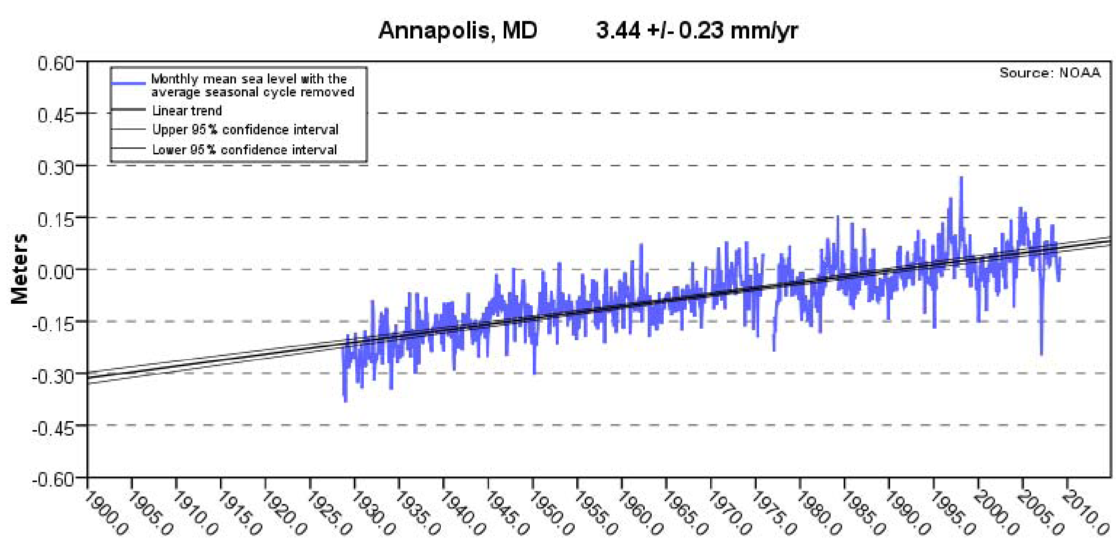


FIGURE 8

Monthly Mean Sea Level Values, Long-Term Linear Trend, and 95 Percent Confidence Interval at Baltimore, Maryland (8574680)

Values adjusted to exclude regular seasonal fluctuations caused by coastal ocean temperatures, salinities, winds, atmospheric pressures, and ocean currents. The plotted values are relative to the most recent Mean Sea Level datum established by CO-OPS. (NOAA, 2009)

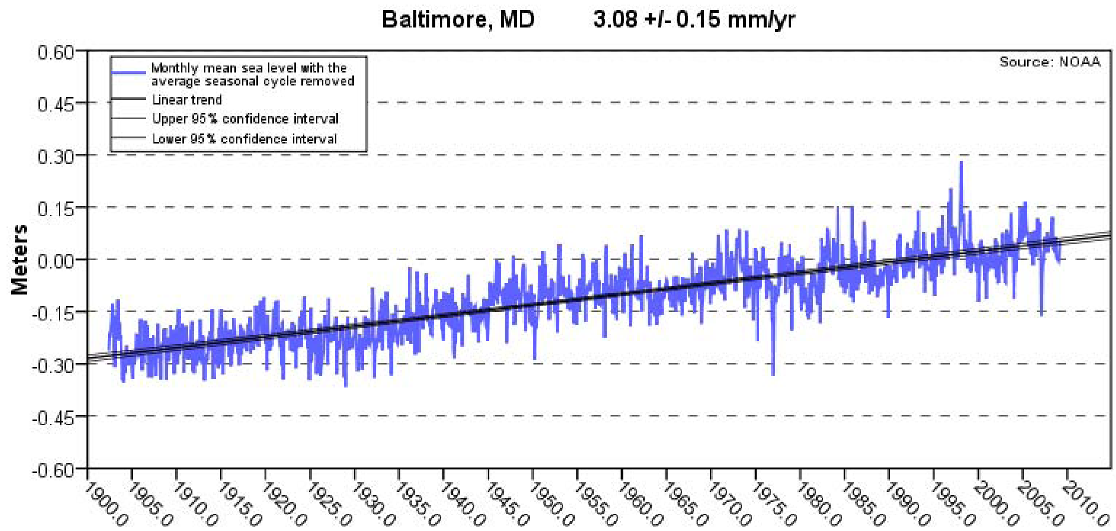
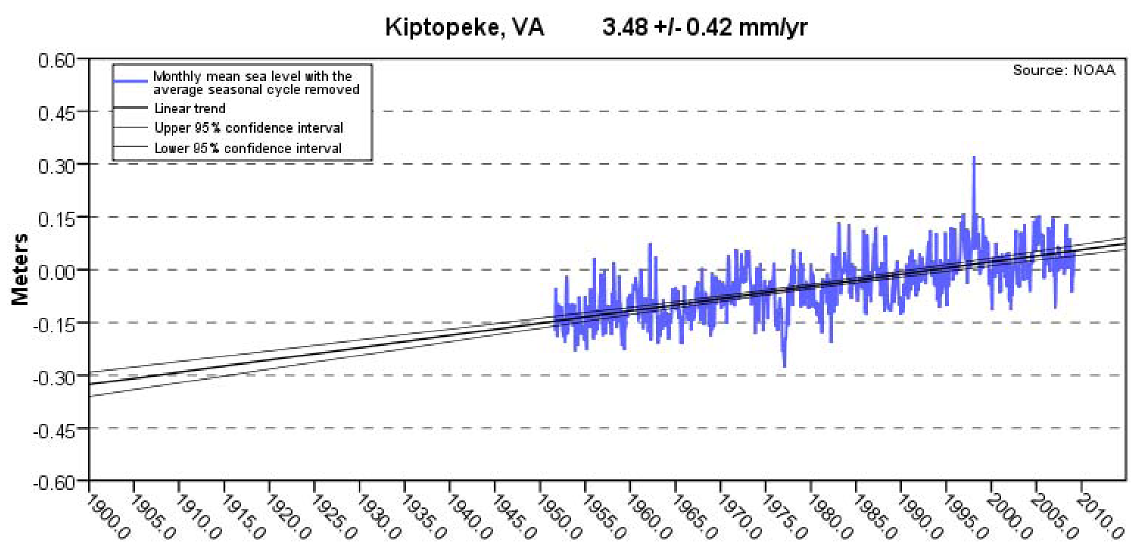


FIGURE 9

Monthly Mean Sea Level Values, Long-Term Linear Trend, and 95 Percent Confidence Interval at Kiptopeke, Virginia (8632200)

Values adjusted to exclude regular seasonal fluctuations caused by coastal ocean temperatures, salinities, winds, atmospheric pressures, and ocean currents. The plotted values are relative to the most recent Mean Sea Level datum established by CO-OPS. (NOAA, 2009)



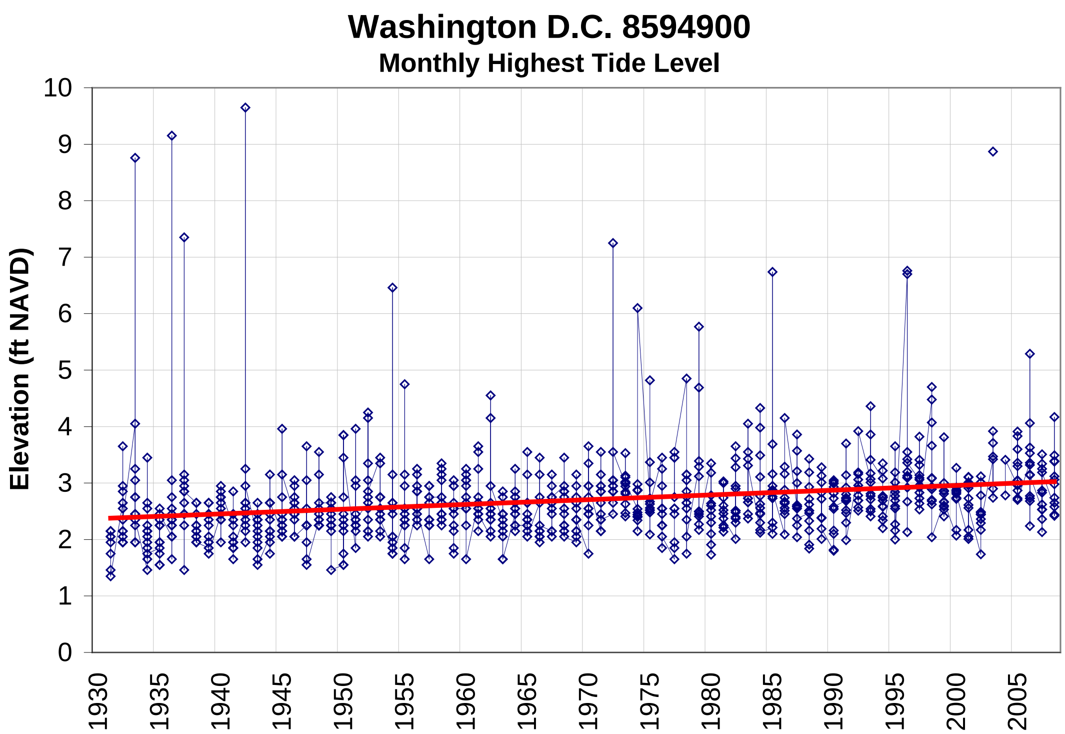
Tidal Extremes and Storms in Chesapeake Bay

Table 6 lists the top ten highest historical tide values at Washington, D.C., between 1931 and 2008, showing that most are related to tropical storm events. Tropical cyclones and extratropical winter cyclones can impose dramatic and long-lasting changes in estuaries. For example, 50 percent of the sediment deposited in the northern Chesapeake Bay between 1900 and the mid-1970s was caused by Tropical Storm Agnes (June 1972) and the extratropical cyclone associated with the Great Flood of (March) 1936 (Hirschberg and Schubel, 1979). In October 2003, winds associated with Hurricane Isabel produced a maximum storm surge of 2.7 meters in the Chesapeake Bay and also mixed the estuary, resulting in biogeochemical and ecological changes felt into the following spring (Roman et al., 2005).

TABLE 6
Top Ten Highest Historical Tide Values at Washington, D.C. 8594900 (1931-2008)

Date	Highest Tide Level (ft) (NAVD 88)	Event
October 1942	9.65	Tropical Storm (unnamed)
March 1936	9.15	“The Great Spring Flood”
September 2003	8.87	Hurricane Isabel
August 1933	8.76	Hurricane (unnamed)
April 1937	7.35	Not available, or event unnamed.
June,1972	7.25	Tropical Storm Agnes
September 1996	6.76	Not available, or event unnamed.
November 1985	6.74	Hurricane Juan
January,1996	6.7	Tropical Storm Fran

FIGURE 10
Monthly Highest Historical Tide Values at Washington, D.C., 8594900



Trenberth et al. (2007) summarized recent studies on tropical cyclone trends, noting a significant upward global trend in their destructiveness (caused by intensity and lifetime increases) since the 1970s, which correlates with sea surface temperature. Christensen et al. (2007) and Meehl et al. (2007) summarized future projections in tropical cyclones and concluded that peak wind intensities will likely increase.

Past and future trends in extratropical cyclones are fairly clear at the hemispheric scale, but not at the regional scale. In the middle latitudes (including the Chesapeake Bay and its watershed), winter extratropical storm frequency has decreased and intensity increased over the second half of the 20th century (McCabe et al., 2001; Paciorek et al., 2002). An analysis of U.S. East Coast extratropical winter storms, however, demonstrated no significant trend in frequency and a marginally significant decline in intensity (Hirsch et al., 2001). Lambert and Fyfe (2006) showed remarkable consistency among GCMs in the future projections of winter extratropical cyclone activity. For the A1B scenario, the multi-model means over the Northern Hemisphere represent a 7 percent decrease in the frequency of all extratropical winter cyclones, and a 19 percent% increase in intense extratropical winter cyclones when comparing the 2081 through 2100 with the 1961 through 2000 periods.

Washington, D.C., Water Level Elevation Extreme Value Analysis

A return frequency analysis was conducted of the historical daily tide data at Washington, D.C. The daily maximum tide values were loaded into the SimCLIM modeling tool (Warrick, 2005), developed by CLIMsystems in New Zealand, and a generalized extreme value (GEV) analysis was performed to determine the return interval of different water level elevations based on the historical tide gauge data. Table 7 shows the estimated water level elevation for different return intervals based on this analysis of the 30-year historical record. Note that the water level elevations reflect the combined effects of tidal variations, storm surge in the Potomac River, and storm flows coming down the Potomac River.

As a point of comparison, the Federal Emergency Management Agency (FEMA) is updating the 100-year flood inundation maps for the Potomac River. The estimated 100-year flood elevation for the Alexandria, Virginia, section of the Potomac River is reported to be 10.0 feet relative to the NAVD 88 (FEMA, unpublished).

TABLE 7
Washington, D.C., Tide Return Intervals and Associated Tide Elevations in Feet. Period of record 1979 through 2009.

Return Interval (Year)	Water Level Elevation (feet)
2	3.703
5	4.595
10	5.410
20	6.418
50	8.156
100	9.879
500	15.880

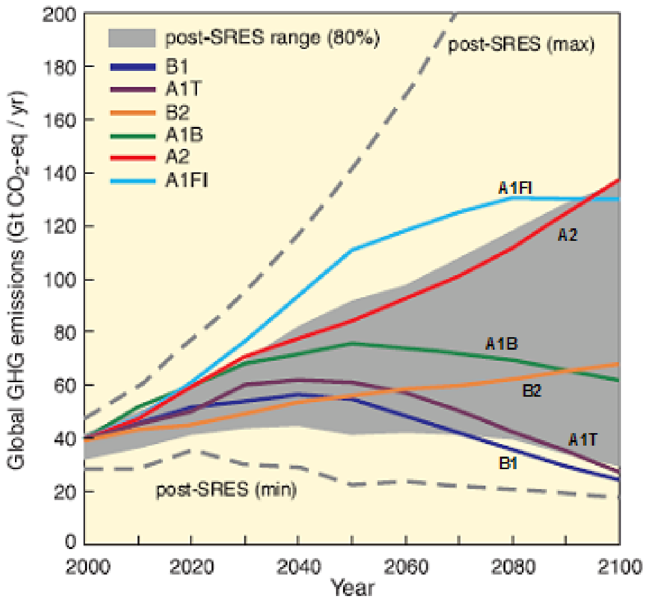
Datum: NAVD 1988

Emissions Scenarios used as Input for Global Climate Change Models

In 2000, the IPCC published a special report on emissions scenarios (SRES) that described a family of six emission scenarios to condition global climate models, shown on Figure 11 (IPCC, 2000). The SRES scenarios cover a wide range of the main driving forces of future emissions, from demographic to technological and economic developments. None of the scenarios in the set includes any future policies that explicitly address climate change, although all scenarios necessarily encompass various policies of other types. A total of six emission scenarios (SRES) were available from the Model for the Assessment of Greenhouse Gas Induced Climate Change (MAGICC) (Wigley, 2008).

To help bound the uncertainty of emission-driven projected climate change, the City sea level rise study used the B1 (low), A1B (medium), and A1FI (high) emissions scenarios for the evaluation period of 1990 through 2100. A complete description of the SRES can be found in Appendix A and in the IPCC SRES (IPCC, 2000).

FIGURE 11
Scenarios for GHG Emissions from 2000 to 2100 in the Absence of Additional Climate Policies (IPCC 2007).



SimCLIM Modeling of Sea Level Rise

The SimCLIM modeling tool (Warrick, 2005), developed by CLIMsystems in New Zealand, provides a tool in which the impacts of climate on the environment can be examined. SimCLIM merges historical climate information with global climate change projections to provide users with the ability to conduct sensitivity analysis and examine sector impacts of climate change.

The SimCLIM Sea level Scenario Generator contains tabular year-by-year output from MAGICC (Wigley et al., 2000), a simple GCM, as forced by the six key SRES greenhouse gas emission scenarios used in the IPCC Third Assessment Report (IPCC, 2001). For each scenario, low, medium, and high projections are provided for global mean changes in temperature, sea level thermal expansion, and sea level total (including ice melt). The corresponding values for atmospheric concentrations of carbon dioxide are also provided.

In general, the low and high uncertainty ranges correspond to the results given in the IPCC Summary for Policymakers (IPCC, 2007), which represent 90 percent uncertainty intervals unless stated otherwise. That is, there is an estimated 5 percent likelihood that the value could be above or below the range. . Best estimates are provided where available. Assessed uncertainty intervals are not always symmetric about the corresponding best estimate.

TABLE 8
Five GCMs and SRES Emission Scenarios Selected for Sea Level Rise Assessments in the Chesapeake Bay.

Five General Circulation Models Selected for Sea Level Rise Projections for the Alexandria, VA Project (Model Developer, Country)	SRES Emission Scenarios
ECHAM5 – (Max Plank Institute for Meteorology, DKRZ, Germany)	A1FI (high)
GFDLCM-21 (Geophysical Fluid Dynamics Lab, USA)	A1B (medium)
UKHADCM3 (Hadley Centre, United Kingdom)	B1 (low)
CCSM-30 (National Center for Atmospheric Research, USA)	
CCCMA-31 (Canadian Climate Centre, Canada)	

General Circulation Model Selection

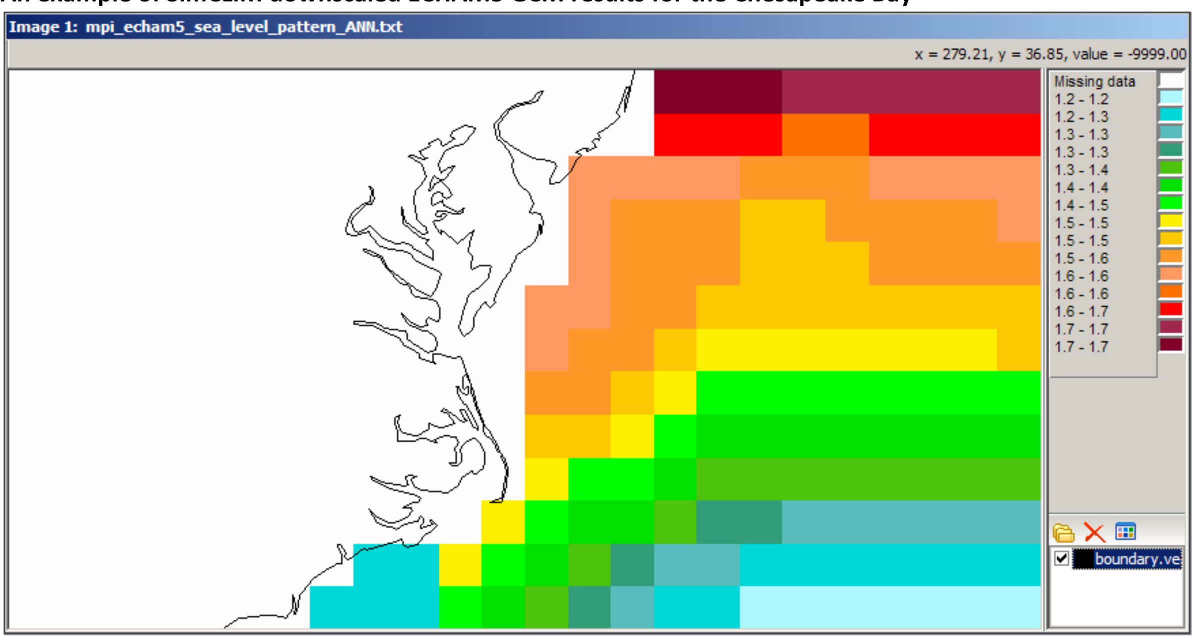
Currently, no definitive ranking of sea level rise models is available in peer-reviewed journals. Of the 13 GCMs sea level rise thermal expansion models available in SimCLIM, five GCMs were selected based on their abilities to represent sea level rise in the Chesapeake Bay area (Table 8). An example of SimCLIM downscaled (1-kilometer resolution) ECHAM5 GCM results for the Chesapeake Bay is shown on Figure 12

GCM results are produced at a coarse resolution, approximately 100 to 200 kilometers, and must be downscaled to capture the effects of local climate characteristics. Statistical downscaling is a two-step process basically consisting of 1) development of statistical relationships between local climate variables (e.g., surface air temperature and precipitation) and large-scale predictors, and 2) application of such relationships to the output of GCM to simulate local climate characteristics.

The SimCLIM application uses statistical downscaling to create 1-kilometer monthly projected “climate surfaces” using historical monthly average interpolated climate elements. The method is fully described by Santer et al. (1990). The historical monthly average climate elements used for the downscaling are further described in Hijmans et al. (2005).

FIGURE 12

An example of SimCLIM downscaled ECHAM5 GCM results for the Chesapeake Bay



Sea Level Rise Analysis Method

The sea level rise process involved two steps. The first step involved assessing the relationship between the mean monthly sea level and mean monthly MHHW trends for the Washington, D.C., tide gage. Monthly MSL for Washington DC is shown on Figure 13. A relationship between MSL and MHHW was derived to merge sea level rise projections with expected high tides in the Washington, D.C., area. The relationship yielded a correlation of 0.9517 (Figure 14) and was deemed suitable for use in translating projected MSL to a projected MHHW.

For each of the five selected GCMs, three SRES emission scenarios low (B1), medium (A1B), and high (A1FI) were run for the period 1990 through 2100. SimCLIM produced 15 annual projections of median sea level rise, 15 sea level rise projections representing the 10 percent non-exceedance threshold, and 15 sea level rise projections representing the 90 percent non-exceedance threshold to bound GCM and SRES uncertainty.

SimCLIM-derived mean sea level rise projections relative to historical trends are shown on Figure 15. The projected median sea level rise from the five GCMs and three SRES scenarios ranges from 1.76 to 2.44 feet (NAVD) by the year 2100. The 10 and 90 non-exceedance percent ranges are 1.33 and 3.35 feet NAVD, respectively.

Using the MSL/MHHW relationship, the projected median MHHW sea level rise from the five GCMs and three SRES scenarios ranges from 3.35 to 4.05 feet (NAVD) by the year 2100. The 10 and 90 non-exceedance percent ranges are 2.94 and 4.96 feet (NAVD), respectively (Figure 16).

FIGURE 13

Historical Observed Monthly Mean Sea Level Values at Washington, D.C. (8594900) (1931 through 2008)

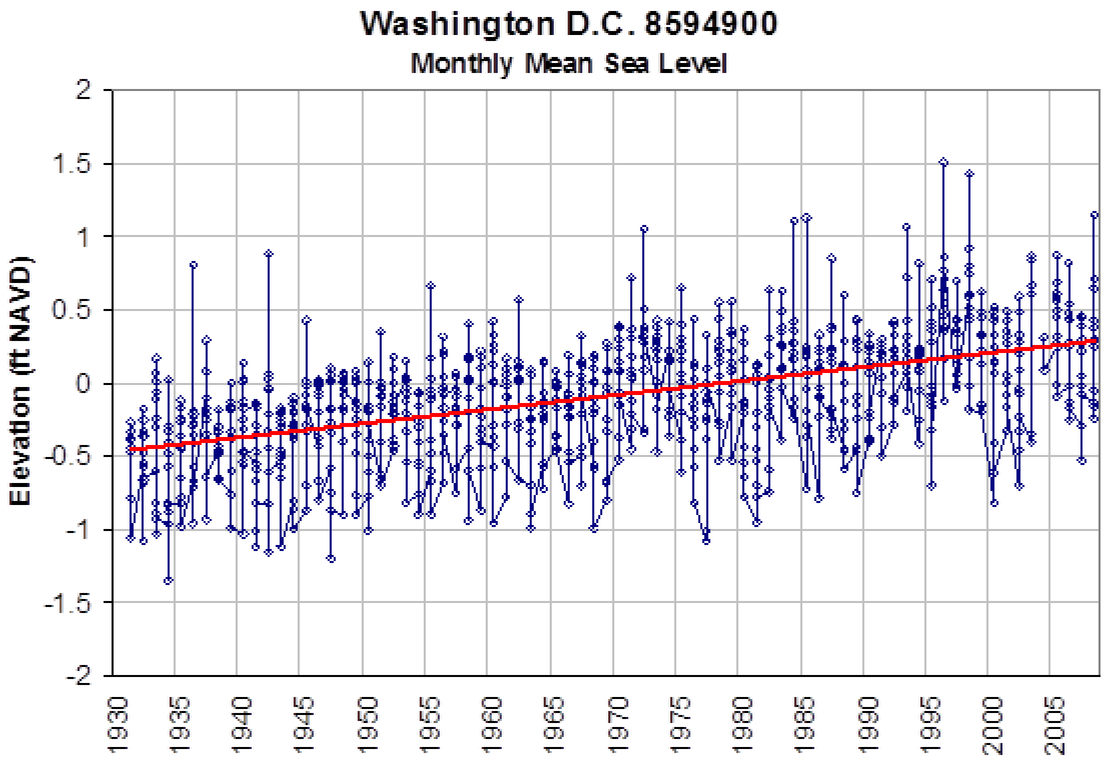


FIGURE 14

Linear Relationship between Historical Observed Mean Sea Level Values and Mean Higher High Water Values at Washington, D.C. (8594900) (1978 – 2008)

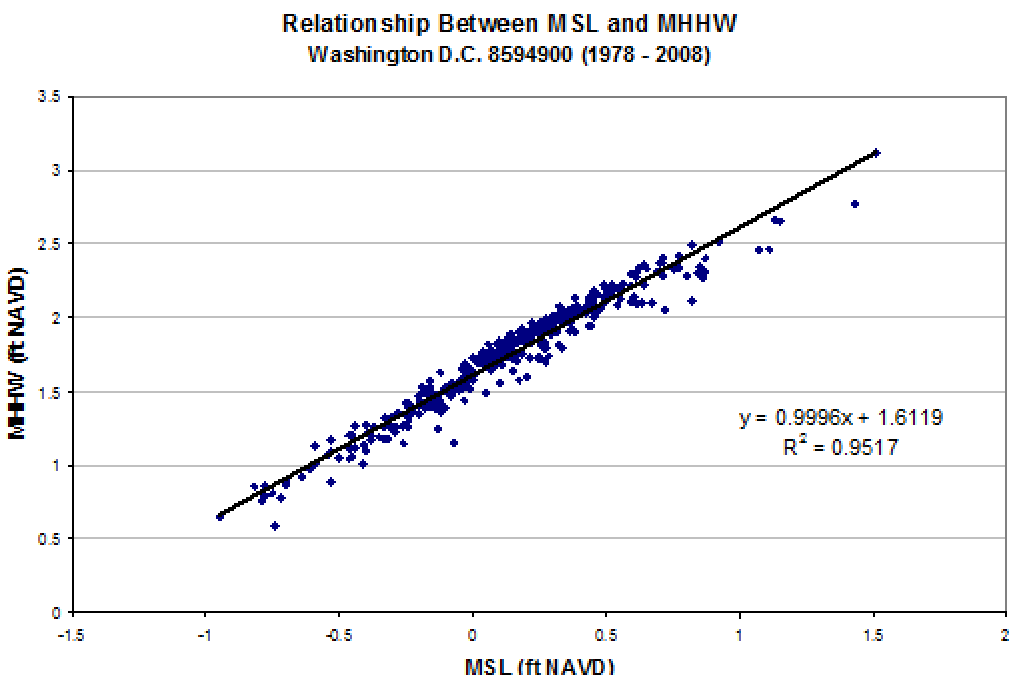


FIGURE 15

Projected Mean Sea Level (1990 through 2100) Relative to Observed Historical Values and Trend (1931 through 2008) at Washington, D.C. (8594900)

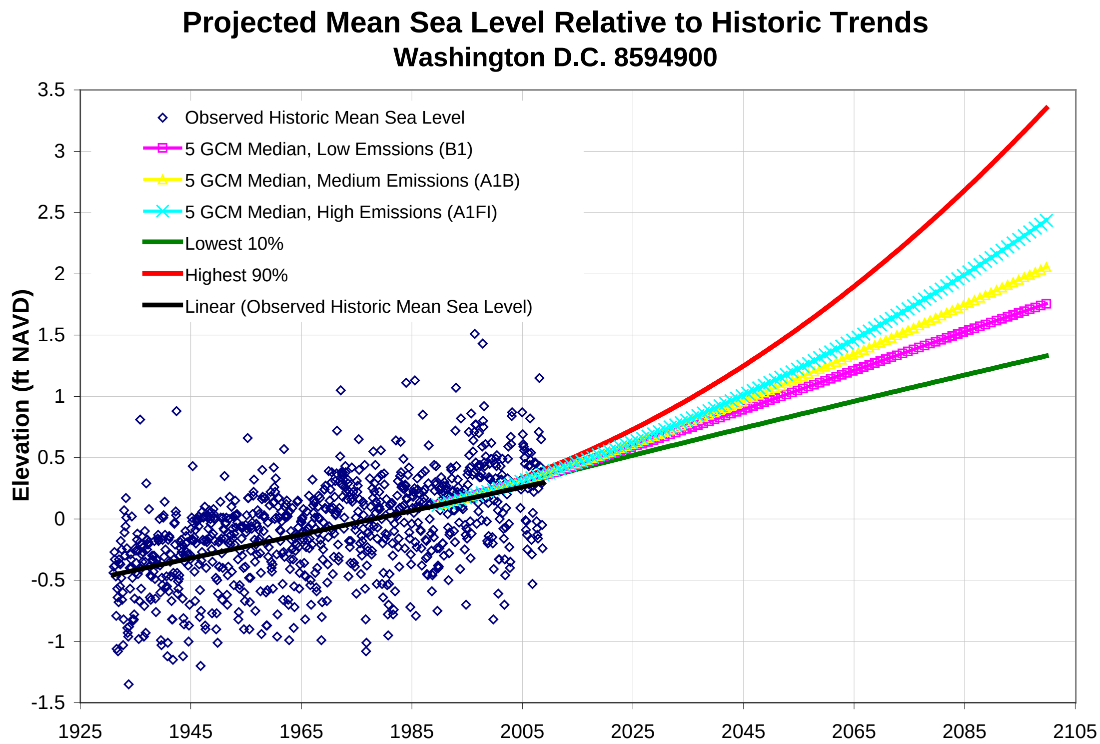
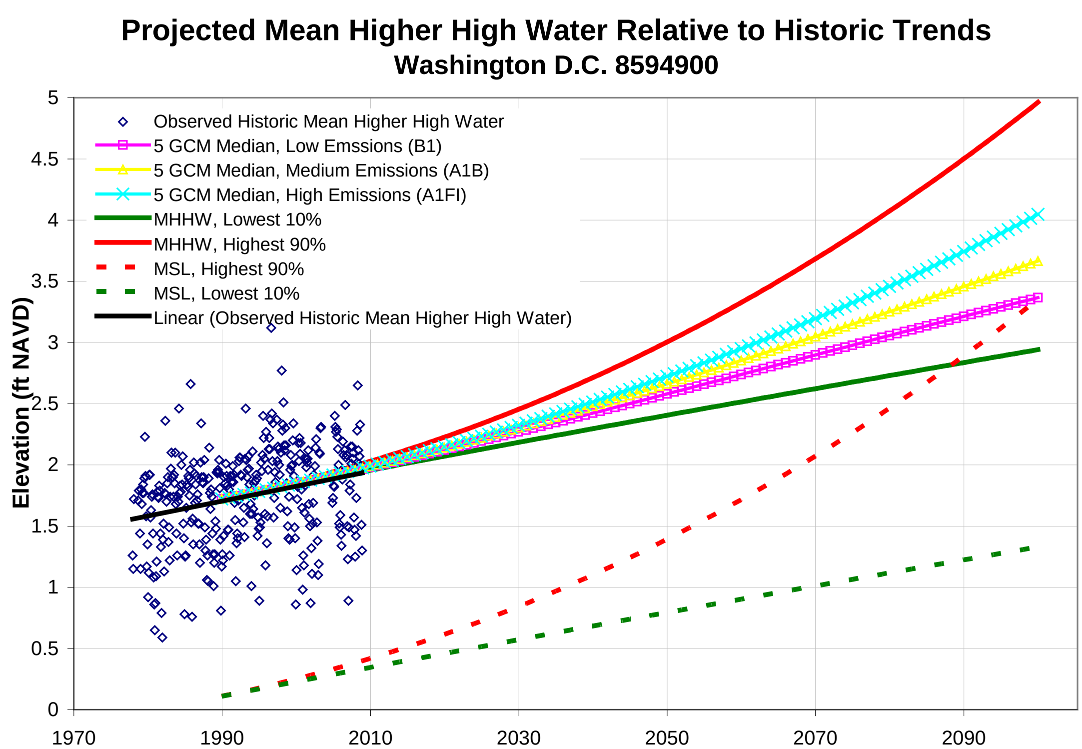


FIGURE 16

Derived Projection of Mean Higher High Water Levels (1990 through 2100) Relative to Observed Historical Values and Trend (1978 through 2008) at Washington, D.C. (8594900)



Summary and Conclusions

Results from five GCMs using low, medium, and high greenhouse gas emission scenarios were used to generate projected changes in mean high water and MHHW at the Washington, D.C., gauge near the City for the years 2050 through 2100.

The projected median sea-level rise from the five GCMs and three greenhouse gas scenarios ranges from 1.76 to 2.44 feet (NAVD) by the year 2100. The 10 and 90 non-exceedance percent ranges are 1.33 and 3.35 feet NAVD, respectively.

The projected median MHHW sea-level rise from the five GCMs and three greenhouse gas scenarios ranges from 3.35 to 4.05 feet (NAVD) by the year 2100. The 10 and 90 non-exceedance percent ranges are 2.94 and 4.96 feet (NAVD), respectively.

A review of relevant literature on sea-level rise in the Chesapeake Bay area was conducted. The literature indicated a range of sea-level rise from 2.7 to 3.4 feet in one study, and from 1.6 to 4.6 feet in another study by 2100. The literature generally corroborates the projections developed in this study.

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Acronyms and Abbreviations

CCSP	U.S. Climate Change Science Program
City	City of Alexandria, Virginia
cm	centimeter
FEMA	Federal Emergency Management Agency
GCM	general circulation model
GEV	generalized extreme value
IDF	intensity, duration, and frequency
IPCC	Intergovernmental Panel on Climate Change
MAGICC	Model for the Assessment of Greenhouse Gas Induced Climate Change
MCCC	Maryland Commission on Climate Change
MHHW	mean higher high water
MIS-5e	Marine Isotope Stage-5e
NAVD 88	North American Vertical Datum of 1988
NOAA	National Oceanic and Atmospheric Administration
NWF	National Wildlife Federation
SLAMM	Sea Level Affecting Marshes Model
SRES	special report on emissions scenarios

Appendix A
Special Emissions Scenarios (SRES) Storylines

Special Emissions Scenarios (SRES) Storylines

A1. The A1 storyline and scenario family describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building, and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system. The three A1 groups are distinguished by their technological emphasis: fossil intensive (A1FI); non-fossil energy sources (A1T); or a balance across all sources (A1B) (where balanced is defined as not relying too heavily on one particular energy source, on the assumption that similar improvement rates apply to all energy supply and end-use technologies).

A2. The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing population. Economic development is primarily regionally oriented and per capita economic growth and technological change more fragmented and slower than other storylines.

B1. The B1 storyline and scenario family describes a convergent world with the same global population as in the A1 storyline (peaks in mid-century and declines thereafter), but with rapid change in economic structures toward a service and information economy, with reductions in material intensity and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social, and environmental sustainability, including improved equity, but without additional climate initiatives.

B2. The B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with continuously increasing global population at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the A1 and B1 storylines. While the scenario is also oriented towards environmental protection and social equity, it focuses on local and regional levels.